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PLASTIC SET OF SMOOTH LARGE RADII OF CURVATURE THERMAL CONDUCTANCE SPECIMENS AT LIGHT LOADS

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Abstract

Thermal contact conductance test data at high vacuum were obtained from two Armco iron specimens having smooth, large radii of curvature, convex, one-half wave length surfaces. The data are compared with calculations based on two macroscopic elastic deformation theories and an empirical expression. Major disagreement with the theories and fair agreement with the empirical expression resulted. Plastic deformation of all the contacting surfaces was verified from surface analyzer statistics. These results indicate that the theoretical assumption of macroscopic elastic deformation is inadequate for accurate prediction of heat transfer with light loads for Armco iron specimens similar to those used in this investigation.

Introduction

Smooth metal surfaces having large radii of curvature joined together under light load by rivets, bolts, etc. are commonly found in spacecraft. Such joints act as paths through which heat is transferred. The theories of A. M. Clausing and B. T. Chao(1) and B. B. Mikic and W. M. Rohsenow(2) are frequently used to predict the coefficient of thermal contact conductance for contacting surfaces under high vacuum conditions at light loads. Two of the assumptions made in these theories may not be strictly applicable to specimens having smooth contacting surfaces with large radii of curvature. The first assumption specifies that macroscopic elastic deformation occurs during the formation of such joints with an associated effect on the heat transfer rate. The second specifies that the minute contact spots which form during the formation of a joint are uniformly distributed over the contacting area. Discussions in Refs. 1 and 2 concerning test results indicate possible invalidity of these assumptions. Clausing and Chao(1) indicate consistently poor theoretical agreement with data from several specimens having smooth large radii of curvature. Also, they note that plastic deformation occurred for three magnesium specimens which had smooth surfaces with large radii of curvature. In Ref. 2 Mikic and Rohsenow indicate that their theoretical expression might have serious limitations because it is dependent on the uniform distribution of the contact spots over the contacting area. Mikic and Rohsenow conclude that if the distribution of the contact spots were not uniform it would have the same effect on the conductance as an equivalent type of waviness. They present experimental data from several rough nominally flat (i.e., no waviness) specimens to substantiate the effect. Because of the lack of agreement between experimental data and the theories of Ref. 1 and other similar theories, L. S. Fletcher and D. A. Gyorog(3) developed an empirical expression for the coefficient of thermal contact conductance. They show correlation between their expression and experimental data and the data of seven other investigators including Clausing and Chao(1) to within a mean deviation of 24 percent. Because of this correlation with an immense amount of data, their work is of particular interest here.

This paper presents experimental test data obtained from two Armco iron cylindrical specimens having smooth, convex, one-half wave length contacting surfaces with large radii of curvature which show the variation of the coefficient of thermal contact conductance with apparent contact pressure in the light to moderate range (0.45×10^6 to 3.44×10^6 N/m^2). The data were gathered during two loading and unloading sequences of each specimen at a constant interface temperature (369 K) under high vacuum conditions (1.2×10^{-7} torr). Results are compared with the theories of A. M. Clausing and B. T. Chao(1) and B. B. Mikic and W. M. Rohsenow.(2) Also, a comparison is made with the empirical solution of L. S. Fletcher and D. A. Gyorog.(3)

Symbols

a	radius of macroscopic circular contact area
A	apparent contact area
b	radius of cylindrical specimen
d	half-wave height of specimen's spherical cap
d'	surface parameter
E	modulus of elasticity
FD	flatness deviation
$f(x_L)$	function representing the effect of neighboring contact points on the flow of heat through a point contact
H	micro-hardness of the softer of the two contacting surfaces
h	coefficient of thermal contact conductance
k	harmonic mean of the coefficient of thermal conductivity
L	length of upper or lower portion of a specimen
L_s	one-half the spherical surface wave length
n	number of contacts spots per unit area

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P	apparent contact pressure
$\dot{Q}$	heat transfer rate
r	radius of curvature of the contact surface
RD	rms roughness
T_m	temperature at interface of contact
W	applied load
x_L	the constriction ratio
α	contact area ratio
β	coefficient of thermal expansion
δ	effective surface parameter representing the gap between the contacting surfaces
$(\delta_{max})_{ave}$	maximum average roughness height obtained from total profile traces
ϵ^2	ratio of real to apparent contact area
λ_{eff}	effective diameter of the contour area
ν	Poisson's ratio
$\phi(\epsilon)$, $\phi(\lambda_{eff})$	functions which represent approximate finite series solutions of the temperature field at the contact plane

Subscripts:

1	top portion of specimen
2	bottom portion of specimen
i	interface
m	mean
o	no load

Theoretical and Empirical Analyses

The theories of Clausing and Chao[1] and Mikic and Rohsenow[2] both consider distinct contributions to the thermal conductance resulting from the plastic and elastic deformation of the contacting surfaces. Specifically, the roughness of a surface is assumed to deform plastically while the waviness is assumed to deform elastically. Asperities produced by machine tools in the forming of surfaces are called roughness (microscopic irregularities); and surface irregularities having wave lengths generally greater than 0.080 centimeters are called waviness (macroscopic irregularities). Though both theories consider the effects of these deformations the final form of the Clausing and Chao solution expresses the roughness contribution only approximately, therefore, only the waviness contribution of their theory (macroscopic theory) will be described here.

Clausing and Chao's Macroscopic Theory

In 1963 A. M. Clausing and B. T. Chao[1] presented their macroscopic theory of constrictive resistance. The constrictive resistance is defined as the reciprical of the product of the apparent contact area, A, and the coefficient of thermal contact conductance, h. The apparent contact area is equal to the cross-sectional area of their cylindrical model. The theory applies to contacting surfaces loaded in the light to moderate range at high vacuum conditions, where it is assumed that elastic deformation of the macroscopic area of contact of each member occurs. Their model is shown in Fig. 1 which is similar to one appearing in Ref. 1. The theory considers the contact region between two cylinders of length L and identical radius b placed end to end. The ends of the cylinders in the contact plane have radii of curvature r_1 and r_2 (top and bottom, respectively) as shown in Fig. 1. A single large, macroscopic, circular contact area of radius a is assumed to be concentric with that of the apparent contact area. Thus the noncontact region is an annulus whose inside and outside radii are a and b, respectively. Inside the macroscopic contact a high density of microcontact areas is assumed. The microcontact areas are assumed circular, of the same radius, and uniformly distributed over the single macroscopic spot. To determine the change of macroscopic contact area with load, the surfaces are assumed to approximate spherical caps; thus the Hertzean solution[4] can be applied. Therefore, the Clausing and Chao macroscopic theory predicts the coefficient of thermal contact conductance between surfaces having a spherical contour of one-half wave length. The form of the solution taken from Ref. 1 and used in this paper is

$$\frac{hb}{k} = \frac{2x_L}{\pi f(x_L)} \qquad (1)$$

where the limits of its application are

$$\left\{ \begin{matrix} L/b > 0.6 \\ x_L < 0.65 \end{matrix} \right\}$$

k is the harmonic mean of the coefficient of thermal conductivity of the two contacting materials evaluated at their contact interface, and $f(x_L)$ represents the effect of neighboring contact points on the flow of heat through a point contact. $f(x_L)$ is evaluated from

$$f(x_L) = 1 - 1.40925\, x_L + 0.29591\, x_L^3 + 0.05254\, x_L^5 + 0.02105\, x_L^7 + 0.01107\, x_L^9$$

where x_L is the constriction ratio or equivalently the square root of the ratio of the contact area to the apparent contact area. For two spherical surfaces in contact x_L is evaluated from

$$x_L = \left[\frac{3W}{4\, b^3} \left(\frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \right) \left(\frac{1}{r_1} + \frac{1}{r_2} \right)^{-1} \right]^{1/3} \qquad (2)$$

where ν_1 and ν_2 are Poisson's ratio which for most metals one may assume $\nu_1^2 = \nu_2^2 = 0.1$, E_1 and E_2 are the moduli of elasticity, W is the applied load, and r_1 and r_2 are the radii of curvature of the spherical surfaces. In the derivation of this equation Clausing and Chao indicate that the dimensions of the bodies in contact were assumed large in comparison with the radius of the macroscopic contact area. For this reason, Eq. (2)

can be applied to the macroscopic contact model only for small values of x_L. On the basis of several tests reported by them, Eq. (2) was found applicable for x_L less than approximately 0.65. The result of a study performed by them to determine the influence of the length of each portion of the cylindrical specimen on the macroscopic conductance indicated that for values of L/b greater than approximately 0.6 the conductance was unaffected.

Mikic and Roshsenow's Theory

In 1966 B. B. Mikic and W. M. Rohsenow[2] presented methods for predicting the coefficient of thermal contact resistance for four different types of surfaces, however, only the rough and spherically wavy type will be considered here. The thermal contact resistance is presented in Ref. 2 as the reciprical value of the thermal contact conductance. Mikic and Rohsenow consider the surfaces to be pressed together with intimate contact occurring only at a discrete number of locations called contact spots which are uniformly distributed over the contact surface. The spots are all assumed to be circular, flat, and have the same area. These spots introduce the concept of surface asperity roughness into their model. The contact spots are assumed confined inside contour areas which in turn have their own distribution. The contour areas introduce the concept of waviness into the model. For the specific case considered here, the contour areas are assumed to approximate spherical segments. The surface analysis assumes the existence of an ensemble of the surface roughness-only profiles, all taken from one surface, from which one can deduce statistical properties of the surface and, therefore, a random process which possesses a probability density function. The random process is assumed stationary, i.e., the statistical properties of the ensemble of surface profiles are invariant under arbitrary displacement over the surface. In addition, the probability density of the height and slope of the profiles are independent and the surface height is assumed to have a standard normal (Gaussian) distribution. From this analysis the number of contacts per unit area and hence the real area of contact and the effective diameter of the contour areas are determined. In the thermal analysis the temperature distribution and implicitly the thermal contact resistance is specified by the Laplace differential equation (for steady state conditions and thermal conductivity independent of temperature). Because heat is assumed to flow only through flat contact spots, mixed boundary conditions exist at the surface and the temperature field at the contact plane is obtained by the method of superposition of an infinite number of heat sources equally spaced on the contact surface which extends to infinity.

The form of the prediction of the conductance taken from Ref. 2 for two rough and spherically wavy surfaces exposed to a vacuum environment is

$$h = \frac{1}{\dfrac{8\phi(\epsilon)}{k\epsilon\sqrt{\pi n}} + \dfrac{4\phi(\lambda_{eff})L_s}{k\lambda_{eff}}} \qquad (3)$$

The left and right hand terms in the denominator of Eq. (3) represent the effect due to the plastic deformation of the surface roughness and the elastic deformation of the surface waviness, respectively. In Eq. (3) h is the coefficient of thermal contact conductance, ϵ^2 is the ratio of the real to apparent contact area, n is the number of contact spots per unit area, L_s is equal to one-half the spherical surface wave length, λ_{eff} is the effective diameter of the contour area, and k is the harmonic mean of the coefficient of thermal conductivity of the two contacting materials evaluated at their interface of contact. $\phi(\epsilon)$ and $\phi(\lambda_{eff})$ are factors which represent the approximate finite series solution of the temperature field at the contact plane. For a more detailed description of the parameter λ_{eff}, which involves statistical quantities, refer to Ref. 2. The effective to apparent area ratio of a contour area, ϵ^2, is related to the apparent contact pressure by assuming that the surface asperities deform plastically. Therefore,

$$\epsilon^2 = \frac{P}{H(\lambda_{eff})} \qquad (4)$$

where P is the apparent contact pressure and H is the micro hardness of the softer of the two contacting surfaces.

In a discussion of the limitations of the prediction of the conductance, the authors point out that the assumption of the same size and uniformity of distribution of the contact spots over the apparent contact area might have serious limitations on the accurate prediction of the coefficient of thermal contact conductance especially at light pressures. The degree of nonuniformity has the same effect on the conductance as some equivalent type of waviness. Experimental results from several nominally flat specimens were presented to demonstrate this effect.

Fletcher and Gyorog's Empirical Solution

In 1970 L. S. Fletcher and D. A. Gyorog[3] presented an expression for the prediction of the thermal conductance of similar contacting metal surfaces in a vacuum environment. Fletcher and Gyorog point out that although theoretical and experimental studies concerning heat transfer phenomenon in solid materials have resulted in many useful techniques for analysis, few attempts have been directed at the correlation of existing experimental data and thus the prediction of contact conductance. In their study the experimental results for smooth, medium, rough, and smooth to rough contacts of aluminum, stainless steel, brass, and magnesium were used to provide information for the development of an empirical solution.

To classify the contact surfaces used in their study, a surface parameter, d', was defined in terms of its rms roughness and flatness deviation. The contact between surfaces was assumed to occur at the mean surface height of the smoother surface. The contact surface parameter is defined as

$$d' \equiv (FD + 2RD)_{\substack{\text{rough}\\ \text{surface}}} - \frac{1}{2}(FD + 2RD)_{\substack{\text{smooth}\\ \text{surface}}} \qquad (5)$$

where FD is the flatness deviation, and RD is the rms roughness.

From previous work by Fletcher a theoretical expression for the conductance, h, was developed for a single contact and is of the form

$$\frac{h\delta}{k_m} = \frac{\alpha}{1 - \alpha} \tag{6}$$

where α is the contact area ratio, δ is an effective surface parameter representing the gap between the contacting surfaces, and k_m is the mean value of the thermal conductivity. From Eq. (6) and an analysis of their experimental data in dimensionless form, the value of a no-load surface parameter δ_o for each of the surface configurations was determined. The no-load surface parameter δ_o resulted by assuming that the differences in the test data were due only to differing no-load surface conditions. The values of δ_o for all specimens were plotted as a function of the contact surface parameter, d'. From this it was evident that the no-load surface parameter, δ_o, was related to the contact surface parameter, d', and thus to the measured quantities of flatness deviation and roughness.

This work along with some further analysis of the no-load surface parameter, δ_o, and the effective surface parameter, δ, led to the final form of the conductance expression

$$h = k_m e^{177(P\beta T_m b)/(E\delta_o)} \left[5.22\times10^{-6} \frac{\delta_o}{b} + 0.036 \frac{P\beta T_m}{E}\right]^{0.56} \tag{7}$$

where P is the apparent contact pressure, β is the coefficient of thermal expansion, T_m is the mean temperature at the interface of contact, b is the radius of the specimen, and E is the modulus of elasticity.

The suggested form of δ_o is given by

$$\delta_o = 20.45 + 8.06\times10^{-2}d' - 1.58\times10^{-5}(d')^2 + 1.36\times10^{-9}(d')^3$$

where δ_o and d', the contact surface parameter, are in microinches.

Fletcher and Gyorog note that the expression for the conductance, i.e., Eq. (7), includes possible radiation effects as the apparent contact pressure is reduced to zero. Also they point out that the expression correlates the experimental data of their investigation and those of seven other investigators whose data comprised approximately 400 points. These data include a range of mean interface temperatures varying from 117 K to 532 K, apparent contact pressures of 6.89×10^4 to 4.82×10^7 N/m^2, surface flatness deviations of 38.1 to 11420 microcentimeters, and surface roughness of 7.6 to 305 microcentimeters. Data for aluminum, stainless steel, brass, magnesium are included. The prediction approximates the data within a mean deviation of 24 percent or less.

The following is a brief discussion of the applicability of the empirical expression developed by Fletcher and Gyorog to the Armco iron test results discussed herein. The test specimens' surface characteristics obtained by Fletcher and Gyorog are listed in Ref. 3, table I. These characteristics are indicated as the average flatness deviation and the average roughness. In all cases but one, the average flatness deviation is 5 times larger than the average roughness of each surface. In the single exception the average flatness deviation is greater than twice the average roughness. This result indicates that none of the surfaces were nominally flat (i.e., not wavy) and at least two thirds of them can be considered smooth and wavy. Therefore, the expression derived by Fletcher and Gyorog would be expected to apply to surfaces which are characterized as wavy with some degree of roughness, but would not apply to surfaces which are characterized as being nominally flat. Their expression, therefore, is particularly applicable to the Armco iron test data presented herein.

Experimental Apparatus and Procedure

Facility. - The two Armco iron specimens were tested in the facility shown in Fig. 2. The tests were performed in a bell jar containing a column composed of a tungsten resistance heated cylindrical heat source and its supporting structure, the test specimen, and a water cooled heat sink. The lower portion of each specimen was especially designed, instrumented, and calibrated against a 99.993 percent pure aluminum (by assay) bar to serve as a heat meter. A pneumatic loading cylinder was located on top of the bell jar and was used to vary the pressure at the contact interface of the test specimen. The heat generated by the heater was transferred across the test interface, through the heat meter, and finally to the water cooled heat sink. The bell jar operates in the 10^{-6} torr pressure range.

Specimens. - The Armco iron cylindrical specimens were 2.54 centimeters in diameter. Their upper portions were 6.97 centimeters long and their lower portions were 12.7 centimeters long.

Surface finish. - The specimens' contacting interface surfaces were produced by lapping and had no lay. Table I presents the average values of the specimens maximum roughness profile heights, $(\delta_{max})_{ave}$ (defined in ref. 5) and their arithmetic average heights A. A. (defined in American Standard ASA B 46.1 - 1962 ASME). The contacting surfaces of the specimens were found to approximate sections of spherical caps having one-half wave length, therefore, the average crest to trough wave height, d, (based on radius of curvature) for the surfaces is also shown.

Thermometry. - The thermocouples were located in the specimens as shown in Fig. 2 and read out on a potentiometer. Type 30 gage, special error limits, chromel-alumel thermocouple wire, butt welded at its ends, was used. These thermocouples have an accuracy of ±1.1 K as guaranteed by the manufacture in the temperature range of their use here. After the tests were completed these thermocouples were calibrated in place on the specimens and were found to be within the manufacture's tolerance for the range of temperatures occurring during the tests. The couples were peened into slots milled into the circumference of each specimen. The slots were approximately 0.076 centimeter long, 0.033 centimeter wide, and at their deepest point were approximately 0.051 centimeter deep. The thermocouple's insulated lead wires were wrapped around the circumference of the specimens to minimize conduction errors in the thermocouple wire. Four couples were located in the upper portions of the specimens at

1.27, 2.54, 3.81, and 5.08 centimeters from the interface of contact. Six couples were located in the specimens' lower portions at 1.27, 2.54, 3.81, 6.35, 8.89, and 11.5 centimeters from the interface of contact.

Test Procedure

The contact conductance tests were performed by varying the interface contact pressures of the specimens in a monotonic increasing then decreasing manner through two complete cycles from approximately 4.5×10^5 to 3.5×10^6 N/m^2 (65 to 500 psi) while maintaining their mean interface temperatures nearly constant at approximately 367 K.

To gain an idea of the time required to establish equilibrium between changes in pressure and/or temperature the test specimens were exposed to steady-state test conditions for periods ranging from 50 to 180 hours between each point while monitoring the variation of the conductance with time. Results from this procedure indicated a minimum of 50 hours was required to reach a stable condition between pressure changes.

Before placing the test specimens in the test column of the bell jar they were cleaned with acetone and baked out in a separate vacuum facility at 10^{-6} torr, through eight 30 minute heating and cooling cycles. Each cycle varied from room temperature to approximately 450 K, well below the recrystallization temperature of Armco iron.

Data Reduction. - The coefficient of thermal contact conductance of each specimen, h, was experimentally determined from the relation

$$\frac{\dot{Q}}{A} = -h(t_{i,2} - t_{i,1}) \qquad (8)$$

where $\dot{Q}/A$ represents the heat transfer rate per unit area across the interface of contact and was determined by a heat balance performed across each specimen's heat meter, discussed in the test apparatus section. The interface temperature difference $(t_{i,2} - t_{i,1})$ was determined by the linear extrapolation of the thermocouple data in the upper and lower portions of each specimen to the interface of contact.

A simplification in this procedure was made by determining the thermal gradient in each portion of a specimen from two thermocouple readings in the same manner as that used by Fried.[6] The gradients determined by this technique were continually checked by plots including all of the thermocouple data from each specimen. The error in temperature difference across the interface introduced by this method was less than 1.1 K from a best line (drawn) through all the thermocouple data from each specimen.

Theoretical Determination of h

Before the theoretical predictions of Refs. 1 and 2 and the empirical expression of Ref. 3 could be applied to determine the coefficient of thermal contact conductance for the test specimens considered here, it is necessary to obtain the roughness profile, total profile, and waviness of each of the contacting surfaces. These surface texture quantities were determined by using a Brush surfanalyzer 1200 system. A description of this system, its operation, and use is given in Ref. 7.

The surface texture quantities, obtained directly from the surfanalyzer traces, were used in the theoretical prediction of Clausing and Chao[1] and also the empirical solution of Fletcher and Gyorog.[3] However, because of the nature of the theoretical prediction of Mikic and Rohsenow[2] it was necessary to use a digital computer program for the case of spherically wavy, rough surfaces in contact. A description of the computer program and its use is given in Ref. 7.

The material properties appearing in the theoretical and empirical expressions used in the calculations were obtained from values in the literature with the exception of the coefficient of thermal conductivity, k, and the microhardness, H. The variation of k with temperature was determined from calibration data taken in the test facility under high vacuum conditions for both Armco iron specimens using a 99.993 percent (by assay) pure aluminum heat meter. The results of this calibration indicate agreement with data from the literature[8] to within 1.5 percent. The contact surfaces' microhardness, H, was measured using a Reichert microhardness tester. These values were found to be larger by approximately 1.7 times the Meyers hardness values appearing in the literature.

Results and Discussion

Experimental cyclic test data are presented for two Armco iron cylindrical specimens having smooth, convex, spherical, one-half wave length contacting surfaces which show the variation of the coefficient of thermal contact conductance with apparent joint contact pressure in the light to moderate range (0.45×10^6 to 3.44×10^6 N/m^2). These data are compared with the theoretical predictions of Clausing and Chao[1] and Mikic and Rohsenow.[2] In addition, the data are compared with the empirical solution of Fletcher and Gyorog.[3]

Cyclic Test Data

Figure 3 presents the experimental test data obtained from specimen 1. This specimen was loaded through two cycles. Its mean interface temperature was kept constant at 369 K with one exception noted at the end of the first loading where it was raised at constant pressure (350 N/m^2) to 477 K. The interface remained at this temperature for 50 hours. Then while maintaining constant pressure it was lowered to 369 K and the pressure cycling was continued. The data obtained for the first loading followed the generally recognized trend exhibited when macroscopic elastic deformation of contacting surfaces takes place. All data following the first loading fell reproduciably on a curve having a slope slightly greater than one which is characteristic after moderate loading pressures have been applied.[9] For the smallest apparent contact pressures, the measured thermal conductances were consistently lower than those obtained initially. Therefore, it may be surmised that the specimen took a permanent set after the initial loading.

The results from specimen 2 obtained under almost identical experimental conditions are shown in Fig. 4. These data appear in Ref. 5 in a slightly different form. Unlike specimen 1, how-

ever, specimen 2 was not exposed to a temperature excursion. The data of specimen 2 follow the accepted trend for elastic deformation. However, closer examination at the lowest loading pressure shows a consistent and reproducible decrease in the conductance perhaps indicating an increasing permanent set.

The contacting surfaces were examined before and after each test with a Brush surfanalyzer. Table I presents each specimen's surface half-wave height, d, obtained before and after the tests. The half-wave height of the top portion of specimen 1 increased by 335×10^{-6} centimeters and the bottom by 210×10^{-6} centimeters. The top of specimen 2 increased by 149×10^{-6} centimeters and the bottom by 122×10^{-6} centimeters. Thus both specimens deformed plastically with the attendent changes in the coefficient of thermal contact conductance noted in the test data. The interface temperature excursion apparently caused specimen 1 to deform more than specimen 2.

In Ref. 1 Clausing and Chao obtained test results from a total of 22 specimens fabricated from brass, magnesium, stainless steel, and aluminum. The data obtained from one of three magnesium specimens indicate that its total equivalent flatness deviation increased from before (89×10^{-6} cm) to after the test (203.2×10^{-6} cm). Where the total equivalent flatness deviation, referred to in Ref. 1, is equal to the sum of each portion of a specimen's half-wave surface height, as used in this paper. With the exception of the three magnesium specimens, no permanent set was detected among these specimens. This was determined by analyzing each contact surface before and after a test using optical interference fringe techniques.

Comparison of Data With Theory

Figures 5 and 6 show the curves determined by applying the theories of Refs. 1 and 2 and the empirical expression of Ref. 3 to the test data obtained during the first loading of specimens 1 and 2, respectively. The calculations were made using the surface statistics listed in table I obtained before the tests were conducted. The coefficients determined from both theories are approximately 3 and 1.5 factors larger than the test data obtained from specimens 1 and 2, respectively. The values determined from the empirical expression are approximately 35 percent lower than the test data obtained from the specimens. The disagreement between specimen's 1 and 2 test results and the theories of Refs. 1 and 2 are similar to several cases discussed in Ref. 1. Clausing and Chao noted better agreement occurred for their specimens having rough surfaces and a total equivalent flatness deviation which varied from 304.8×10^{-6} to 2413×10^{-6} centimeters than for surfaces having a total equivalent flatness deviation which varied from 38.1×10^{-6} to 101.6×10^{-6} centimeters (the range of the Armco iron data presented here). Disagreement with theory occurred for specimens made from magnesium, stainless steel, and aluminum, but not for the brass specimens which had the largest total equivalent flatness deviations.

As an explanation for the disagreement, Clausing and Chao suggest that visible oxide films were inhibiting the flow of heat across their specimens' contacting surfaces. No such oxide films were visible on the Armco iron specimens tested here, however. A discussion by Mikic and Rohsenow in Ref. 2 may serve as a second explanation for the large difference between theory and experiment noted here and in Ref. 1. In the theoretical and empirical analyses section of this paper it is indicated that the theoretical expression of Mikic and Rohsenow, as mentioned by them in Ref. 2, might have serious limitations on the accurate prediction of the conductance. This is dependent on the degree of nonuniformity of the distribution of the contact spots over the apparent contact area. They conclude that if the distribution of the contact spots were nonuniform it would have the same effect on the conductance as an equivalent type of waviness. Though their discussion was in regard to rough nominally flat surfaces in contact, the remarks could also apply to the smooth, wavy case where the distribution of contact spots over the contour area is nonuniform. Like Ref. 2 it is assumed in Ref. 1 that microscopic contacts are distributed uniformly over the contacting surfaces. Referring to the surface statistics obtained from specimens 1 and 2, table I shows that each contact surface had a small number of very tall asperities $(\delta_{max})_{ave}$ (i.e., when compared with each surface's arithmetic average asperity height). As a result, it is probable that their distribution was not uniform over the contact surface, particularly at light loads. Thus as discussed by Mikic and Rohsenow and demonstrated by the test data of Clausing and Chao and the tests conducted here, the assumption that the contact spots are uniformly distributed over the contacting surfaces, made in both Refs. 1 and 2, may be too restrictive for smooth, convex, large radii of curvature surfaces i.e., surfaces having small half-wave heights.

It should be noted here that the test results of specimen 2 were compared in Ref. 5 with the macroscopic theory of Clausing and Chao using the surfanalyzer statistics obtained before the test was performed. However, a mathematical error was made in the application of the theory, therefore, the theoretical curve presented in Ref. 5 is incorrect. The curve presented in Fig. 6 herein and labeled Clausing and Chao, macroscopic theory(1) is the correct curve.

Figures 7 and 8 show the results of applying the theories and the empirical expression based on the surface statistics obtained from the specimens after the tests were made. Though the curves determined from the theories are in good agreement with the data for both specimens, the trend of the curve, in the case of specimen 1, is in poor agreement with the trend of the data. Also the use of the surface statistics obtained after the tests is not permissible since plastic set has been verified by measurements of each specimen's half-wave surface height after testing (table I). Both specimens showed less favorable agreement between the data and the empirical solution when surface statistics obtained after the tests were used.

Empirical Solution. - By comparing Figs. 5, 6, 7, and 8 the empirical solution of Fletcher and Gyorog is seen to be less sensitive, like the test data, to differences in the specimens' half-wave surface heights than the theories of Refs. 1 and 2.

Conclusions

Experimental data showing the variation of the coefficient of thermal contact conductance with apparent contact pressure in the light to moderate range (0.45×10^6 to 3.44×10^6 N/m^2) are presented from two Armco iron cylindrical specimens having smooth, convex, one-half wave length contacting surfaces with large radii of curvature. The data were gathered during two loading and unloading sequences of each specimen at a constant interface temperature of 369 K and under a high vacuum condition of 1.2×10^{-7} torr. The data are compared with the theories of A. M. Clausing and B. T. Chao (1963) and B. B. Mikic and W. M. Rohsenow (1966). Also, a comparison is made with the empirical expression presented by L. S. Fletcher and D. A. Gyorog in 1970.

The conclusions from this study are:

1. The assumption of macroscopic elastic deformation made in both theories is inadequate for an accurate theoretical prediction of the variation of the coefficient of thermal contact conductance with apparent contact pressure for smooth, convex, one-half wave length Armco iron surfaces having large radii of curvature placed in contact and loaded in the light to moderate range. This is based on the cyclic data obtained and the verification that macroscopic plastic deformation of the contacting surfaces occurred during the tests.

2. Major disagreement exists between the theoretical curves (based upon the surface statistics obtained before the tests) and the experimental data obtained during the first loading of the specimens. The disagreement implies that a principle assumption in both theories specifying the distribution of the microscopic contact spots to be uniform over the contacting surfaces may be too restrictive for smooth, convex, large radii of curvature specimens.

3. Better agreement between the curves based on the theories and the experimental data of both specimens resulted when the surface statistics obtained after completion of the tests were used in the theoretical calculations. However, the use of these surface statistics is not permissible since a plastic set occurred during the tests.

4. Correlation of the test data to within 35 percent of the empirical expression of Fletcher and Gyorog was obtained when the surface statistics obtained from both specimens before the test were used. Like the specimens' test data, the empirical solution is less sensitive to differences in the specimens' half-wave surface heights than the solutions based on the theories.

References

1. Clausing, A. M. and Chao, B. T., "Thermal Contact Resistance in a Vacuum Environment," ME-TR-242-1, Aug. 1963, University of Illinois Engineering Experiment Station, Urbana, Ill.

2. Mikic, B. B. and Rohsenow, W. M., "Thermal Contact Resistance," Rep. 4542-41, NASA CR-78319, Sept. 1966, Massachusetts Institute of Technology, Cambridge, Mass.

3. Fletcher, L. S. and Gyorog, D. A., "Prediction of Thermal Contact Conductance Between Similar Metal Surfaces," Paper 70-852, June 1970, AIAA, New York, N. Y.

4. Timoshenko, S. P. and Goodier, J. N., Theory of Elasticity, 2nd ed., McGraw-Hill, New York, 1951, p. 375.

5. McKinzie, D. J., Jr., "Experimental Confirmation of Cyclic Thermal Joint Conductance," Paper 70-853, June 1970, AIAA, New York, N. Y.

6. Fried, E., "Study of Interface Thermal Contact Conductance," R66SD4471, NASA CR-82778, July 1966, General Electric Co., Philadelphia, Pa.

7. Cassidy, J. F. and Mark, H., "Thermal Contact Resistance Measurements at Ambient Pressures of One Atmosphere to 3×10^{-12} mm Hg and Comparison with Theoretical Predictions," Paper 69-629, June 1969, AIAA, New York, N. Y.

8. Anon., "Thermophysical Properties Research Center Data Book, Vol. I - Metallic Elements and Their Alloys," 1960, Purdue University, Lafayette, Ind., fig. 1011, curves 2 and 12.

9. Yovanovich, M. M., "Thermal Contact Conductance of Nominally Flat, Rough Surfaces in a Vacuum Environment," Thermophysics and Temperature Control of Spacecraft and Entry Vehicles, Vol. 18 of Progress in Astronautics and Aeronautics, G. B. Heller, ed., Academic, New York, 1966, pp. 773-794.

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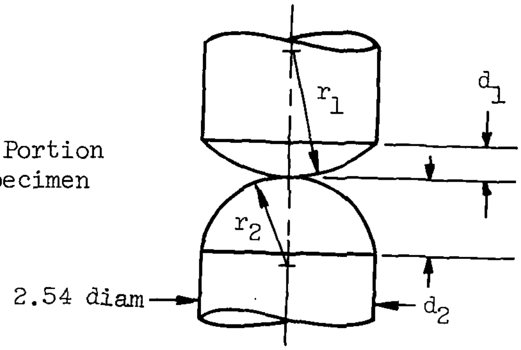
TABLE I. - ARMCO IRON SPECIMENS STATISTICS OBTAINED BEFORE AND AFTER CONDUCTANCE TESTS

Upper and Lower Portion of Armco Iron Specimen



Specimen 1 in Centimeters

	Specimen	d	A. A.	$(\delta_{max})_{ave}$
Before test	Top	46.2×10^{-6}	2.0×10^{-6}	35.1×10^{-6}
	Bottom	53.2×10^{-6}	1.4×10^{-6}	34.8×10^{-6}
After test	Top	381×10^{-6}	5.7×10^{-6}	152.4×10^{-6}
	Bottom	263.3×10^{-6}	2.5×10^{-6}	62.2×10^{-6}

Specimen 2 in Centimeters

	Specimen	d	A. A.	$(\delta_{max})_{ave}$
Before test	Top	132.6×10^{-6}	3.8×10^{-6}	64.1×10^{-6}
	Bottom	50.8×10^{-6}	11.6×10^{-6}	99.4×10^{-6}
After test	Top	282×10^{-6}	2.8×10^{-6}	136×10^{-6}
	Bottom	173.2×10^{-6}	5.1×10^{-6}	180.2×10^{-6}

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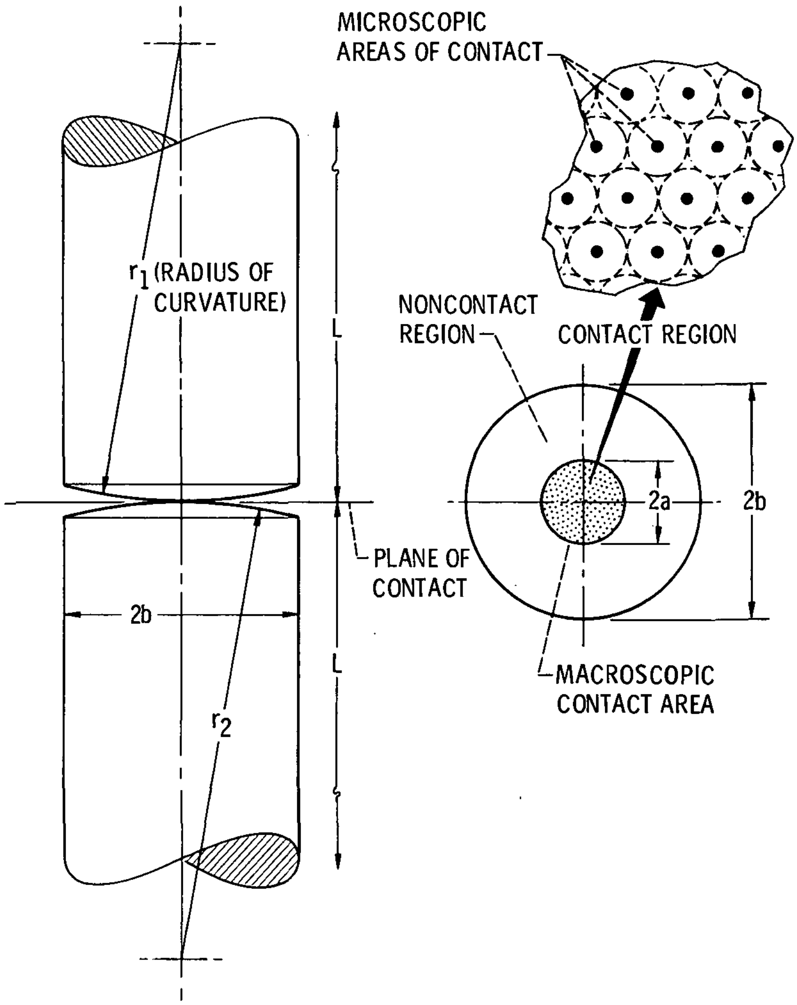
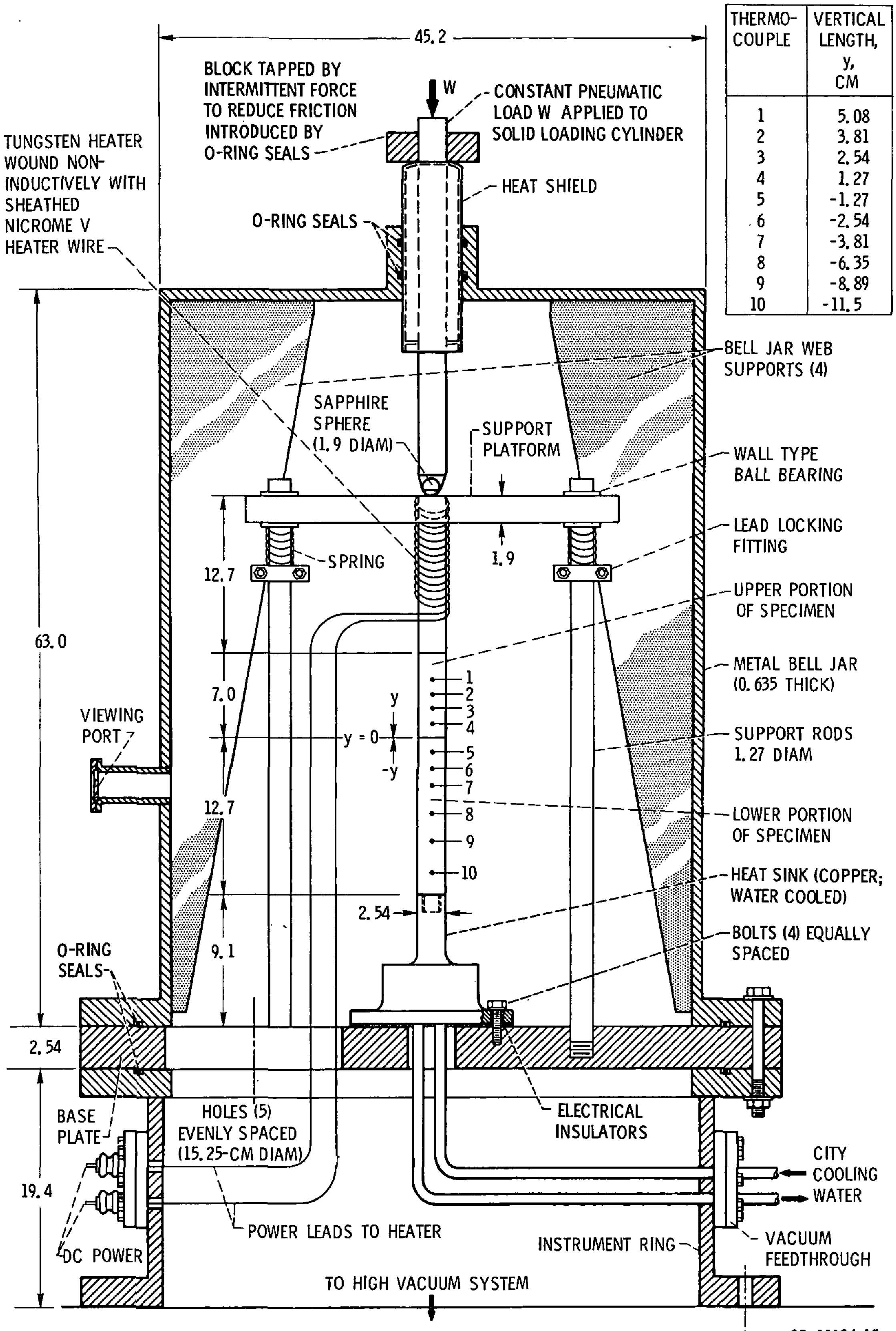


Figure 1. - Macroscopic constrictive resistance model of Clausing and Chao (ref. 1).



THERMO-COUPLE	VERTICAL LENGTH, y, CM
1	5.08
2	3.81
3	2.54
4	1.27
5	-1.27
6	-2.54
7	-3.81
8	-6.35
9	-8.89
10	-11.5

Figure 2. - Internal view of bell jar. (All dimensions are in cm.)

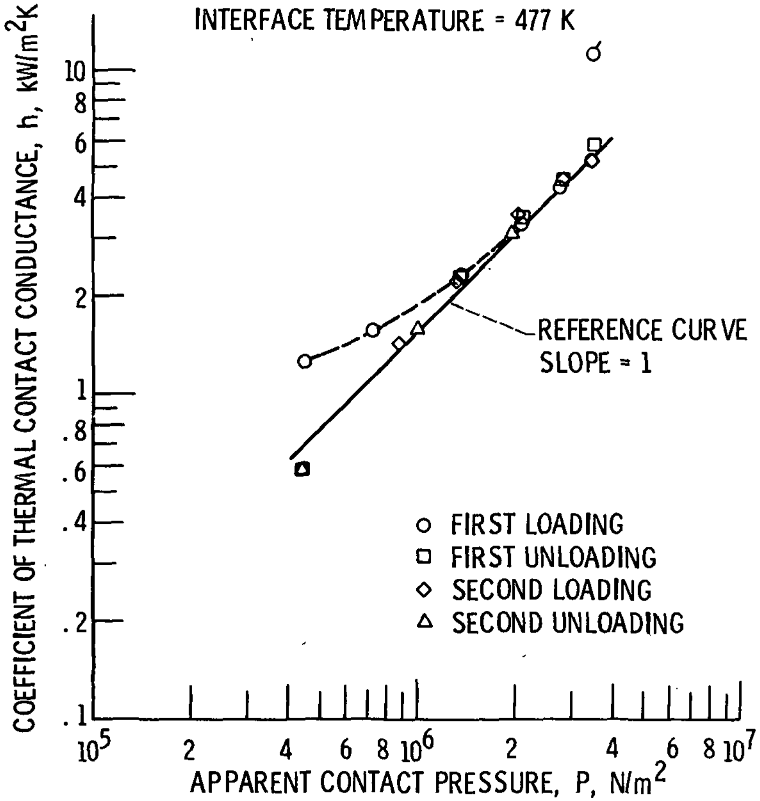


Figure 3. - Coefficient of thermal contact conductance versus apparent contact pressure for Armco Iron - specimen 1. Interface temperature = 369 K.

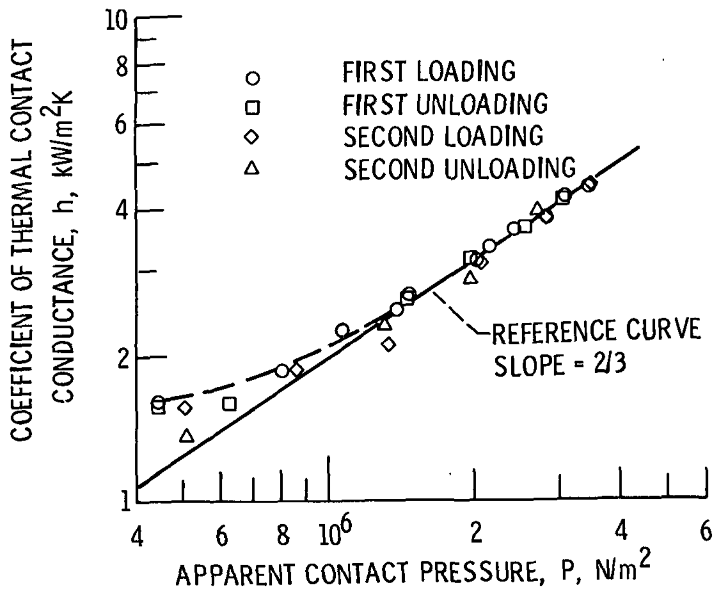


Figure 4. - Coefficient of thermal contact conductance versus apparent contact pressure for Armco Iron - specimen 2. Interface temperature = 367 K.

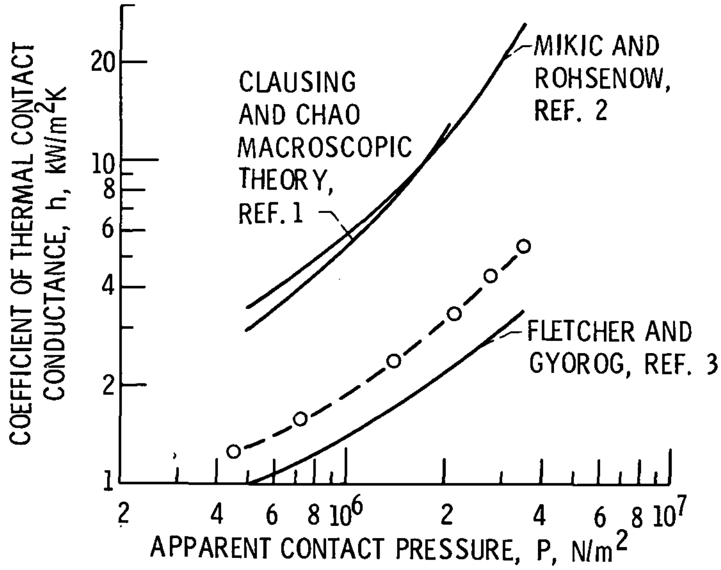


Figure 5. - Coefficient of thermal contact conductance versus apparent contact pressure for Armco Iron specimen 1. Based on surface statistics obtained <u>before</u> the test was run. Temperature of interface = 369 K.

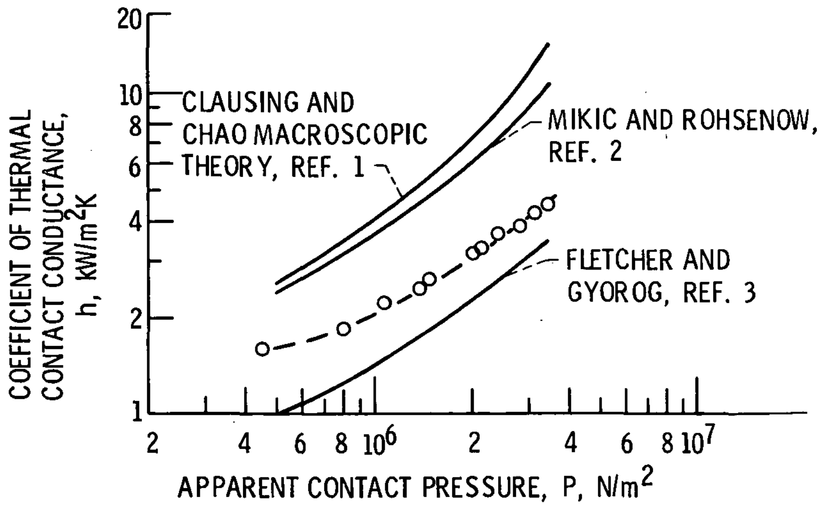


Figure 6. - The coefficient of thermal contact conductance versus apparent contact pressure for Armco Iron specimen 2. Based on surface statistics obtained <u>before</u> the test was run. Temperature of interface = 369 K.

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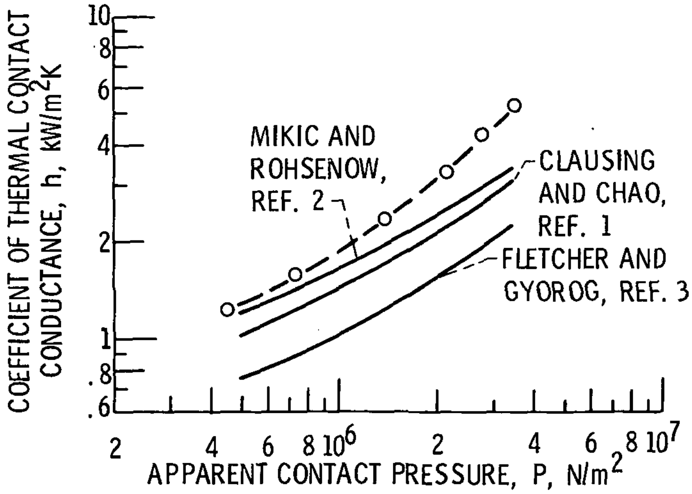

Figure 7. - Coefficient of thermal contact conductance versus apparent contact pressure for Armco Iron specimen 1. Based on surface statistics obtained after the test was run. Temperature of interface = 369 K.

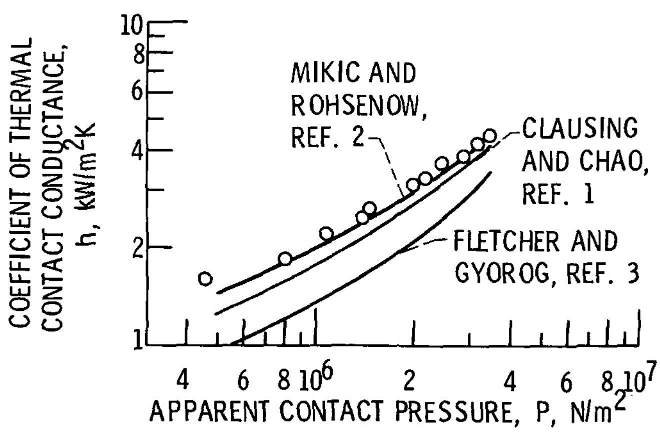

Figure 8. - Coefficient of thermal contact conductance versus apparent contact pressure for Armco Iron specimen 2. Based on surface statistics obtained after the test was run. Temperature of interface = 369 K.